NHDOT SPR2 PROGRAM
RESEARCH PROGRESS REPORT

Project # 26962O	**Report Period:** Year: 2017 ☐Q1 (Jan-Mar) ☐Q2 (Apr-Jun) ☒Q3 (Jul-Sep) ☐Q4 (Oct-Dec)	
Project Title: Incorporating Impact of Aging on Cracking Performance of Mixtures during Design		
Project Investigator: Jo Sias Daniel (Co-PI: Eshan Dave) **Phone:** 603-862-3277 **E-mail:** jo.daniel@unh.edu		
Research Start Date: December 1, 2016	**Research End Date:** September 30, 2018	**Project schedule status:** ☒ On schedule ☐ Ahead of schedule ☐ Behind schedule

Progress this Quarter (include meetings, installations, equipment purchases, significant progress, etc.):

The work conducted in this quarter has mainly focused on the aging, fabrication, specimen preparation, testing, and analysis of four mixtures left from NHDOT project #15680R. The complex modulus, SVECD fatigue, disc-shaped compact tension (DCT) and semicircular bending (SCB) fracture testing were finished for all levels of aging. The results of linear viscoelastic and fracture properties are presented in the Appendix, and were submitted in a TRB paper as well. Four new mixtures (T3,T4, SV-1, and SHS-1) were received from NHDOT; aging on the loose mix asphalt materials from T3 and T4 has begun. Table 1 also shows the summary of project mixtures, information, and the status of testing. Also, 20 field cored samples from Westmoreland #15867 NH12 were received by UNH. Table 2 shows the detailed information for the field cores.

Table 1- Status Summary for Project Mixtures

Mixture ID	Binder PG Grade	NMAS (mm)	%TRB	Status				
				received	aging	fabrication	testing	analysis
WM-S-1	PG 58-28	12.5	1.5					
WM-S-2	PG 58-28	12.5	1.0					
WM-S-3	PG 52-34	12.5	1.0					
WM-S-4	PG 52-34	12.5	1.5					
S-1	PG 58-28	9.5	1.0					
T4	PG 64-28	9.5	1.0					
SHS-1	PG 76-28	9.5	1.0					
SHM-1	PG 70-34	12.5	0					
SV-1	PG 64-28	9.5	0					
T3	PG 58-34	12.5	1.0					
T5	PG 64-28	12.5	1.0					

Done In Progress Not Started

Table 2- Field cores from Westmoreland #15867 NH12

Section	Core number	Height of wearing course(mm)	Height of binder course lift 2 (mm)	Height of binder course lift 1 (mm)
Section 1 Wearing course: PG58-28; 1.5%TRB; NMAS 12.5mm Binder course: PG58-28; 1.5%TRB; NMAS 19.0mm	AC01	51	24	47
	AC02	41	28	60
	AC03	36	65	52
	AC04	43	57	56
	AC05	41	69	78
Section 2 Wearing course: PG58-28; 1.0%TRB; NMAS 12.5mm Binder course: PG58-28; RAP/RAS; NMAS 19.0mm	AC06	45	55	74
	AC07	39	40	41
	AC08	40	61	62
	AC09	37	76	46
	AC10	35	54	0
Section 3 Wearing course: PG52-34; 1.0%TRB; NMAS 12.5mm Binder course: PG52-34; RAP/RAS; NMAS 19.0mm	AC11	42	61	55
	AC12	36	47	51
	AC13	35	50	70
	AC14	37	54	46
	AC15	37	47	45
Section 4 Wearing course: PG52-34; 1.5%TRB; NMAS 12.5mm Binder course: PG52-34; 1.5%TRB; NMAS 19.0mm	AC16	45	49	60
	AC17	50	63	49
	AC18	39	47	53
	AC19	57	38	54
	AC20	45	0	0

Anticipated research next 3 months:
In the coming quarter, the research group plans to continue aging, fabrication, and testing of the available mixtures. UNH will also provide NHDOT with selected aged mixtures for extraction and recovery of binder for subsequent testing.

Circumstances affecting project: Describe any challenges encountered or anticipated that might affect the completion of the project within the time, scope, and budget, along with recommended solutions to those problems.
Nothing at this time.

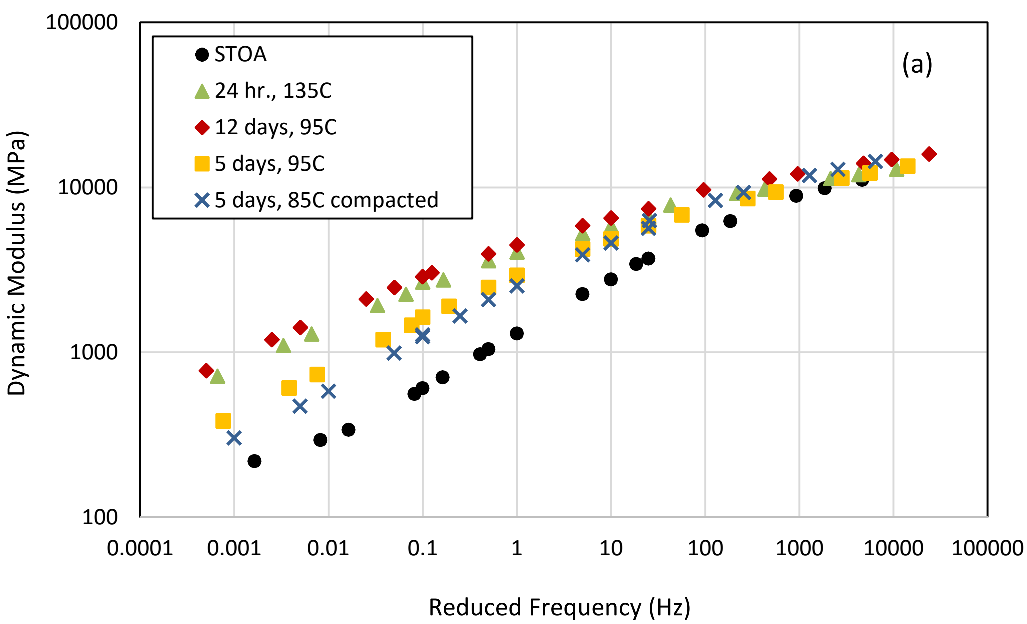
Appendix:

Results and Discussion

Linear Viscoelastic Parameters

Example results of dynamic modulus and phase angle master curves for different aging levels are presented as the average of three replicates for one mixture (PG 52-34, 12.5 mm, 28.3% RAP) in Figure 1. The overall trend is similar for all mixtures evaluated in this study: as the asphalt materials age the stiffness (|*|) increases while the relaxation capability of mixtures, as represented by phase angle (δ), decreases. Statistical testing (t-test) was conducted for dynamic modulus and phase angle results using the measured data obtained from three replicates of each mixture. With a confidence level of 95%, there is a significant difference between |E*| and δ of STOA mixtures with all levels of long term aging. Statistical significance testing also indicate neither dynamic modulus nor phase angle show a statistical difference between 24 hour and 12 days aged mixtures. Also, two shorter levels of aging (5 days on loose mix and 5 days on compacted samples) are not statistically different. It should be mentioned that this comparison was conducted for only four available mixtures. Comparing 12 days and 5 days aging levels, there is a significant difference for all mixtures, except the two 19 mm, PG 52-34 mixtures.

One interesting observation is that the peak phase angle value moves down and left (lower frequencies) as materials age, so that for the two high levels of aging (24 hour and 12 days) the peak phase angle was not measured within the standard testing temperatures (4.4, 21.1, and 37.8°C) and frequencies (25, 10, 5, 1, 0.5, and 0.1 Hz). To capture the peak point for these two levels of aging, the complex modulus testing also included 0.01 Hz at 37.8°C test in addition to standard frequencies and temperatures.



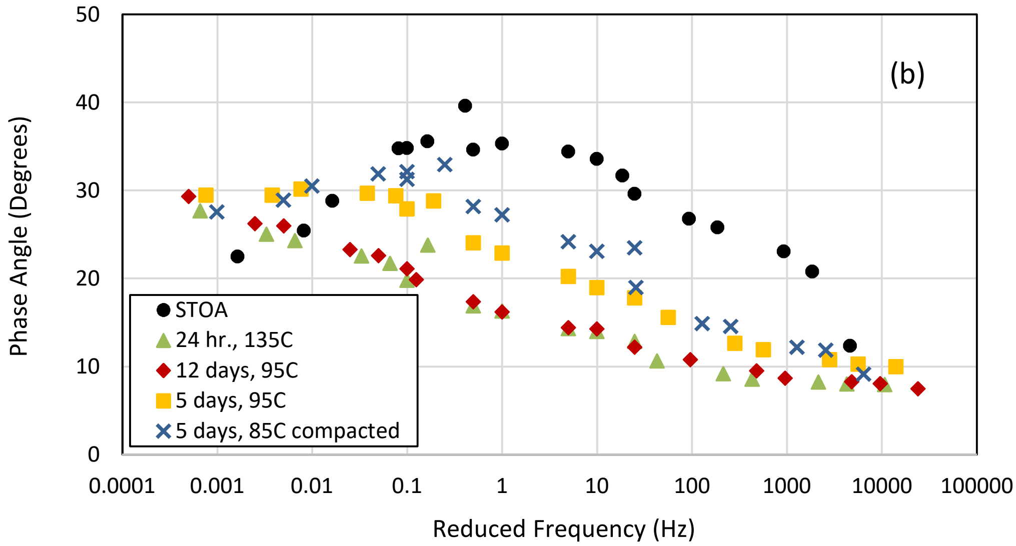


FIGURE 1 Example (a) Dynamic Modulus and (b) Phase Angle Master Curves for Sample Mixture (PG 52-34, 12.5 mm, 28.3% RAP) at Different Aging Levels (Reference Temperature 21.1°C)

Figure 2 compares the average dynamic modulus and average phase angle master curves (in the frequency range of 10^{-5} to 10^{5} Hz) at different long term aging levels versus short term aging values for all of the mixtures evaluated in this study. As expected, all LTOA mixtures have higher dynamic modulus than STOA mixtures. This shows the clear difference between the two intermediate aging levels and the two longer term aging levels, and the similarities of the two long term aging levels at the intermediate frequencies. At the very low and high frequencies, the |E*| of aged mixtures becomes closer to the line of equality, while the difference is greater at intermediate frequencies. Lines representing double and triple the $|E^*|_{(STOA)}$ values are drawn in Figure 2a for added perspective. At frequencies higher than 10 Hz, the dynamic modulus of long term aged mixtures are less than twice the $|E^*|_{(STOA)}$, while at frequencies around 0.01 Hz, the dynamic modulus of long term aged mixtures increase to as high as six times the dynamic modulus of short term aged condition. The reason is that the response of asphalt mixtures at very high frequencies is dominated by elastic behavior which appears to have not been as impacted by long term aging.

The phase angle values of all LTOA mixtures are lower than those of STOA mixture at low and intermediate temperature, which is expected as the relaxation capabilities of mixtures reduce with long-term aging. As shown in Figure 2b, a horizontal shift is observed in phase angle master curves as the aging level increases. At the lower frequencies, the phase angle of STOA mixtures begins to decrease after the inflection point, while the phase angle values of LTOA mixtures are still increasing. At the frequencies lower than the intersection point of STOA and LTOA master curves, the phase angle of STOA mixtures are lower than those of LTOA mixtures (as shown in Figure 1b). As the aging level increases, two curves intersect at a lower frequency. Although it changes from one mixture to another, the longer aged mixtures intersect with STOA mixtures master curves between 0.001 to 0.01 Hz. The intersection of intermediate aged and short term aged mixtures is between 0.01 to 0.1 Hz. At the frequencies lower than these values, the phase angle of LTOA mixtures are higher than phase angle of STOA mixtures.

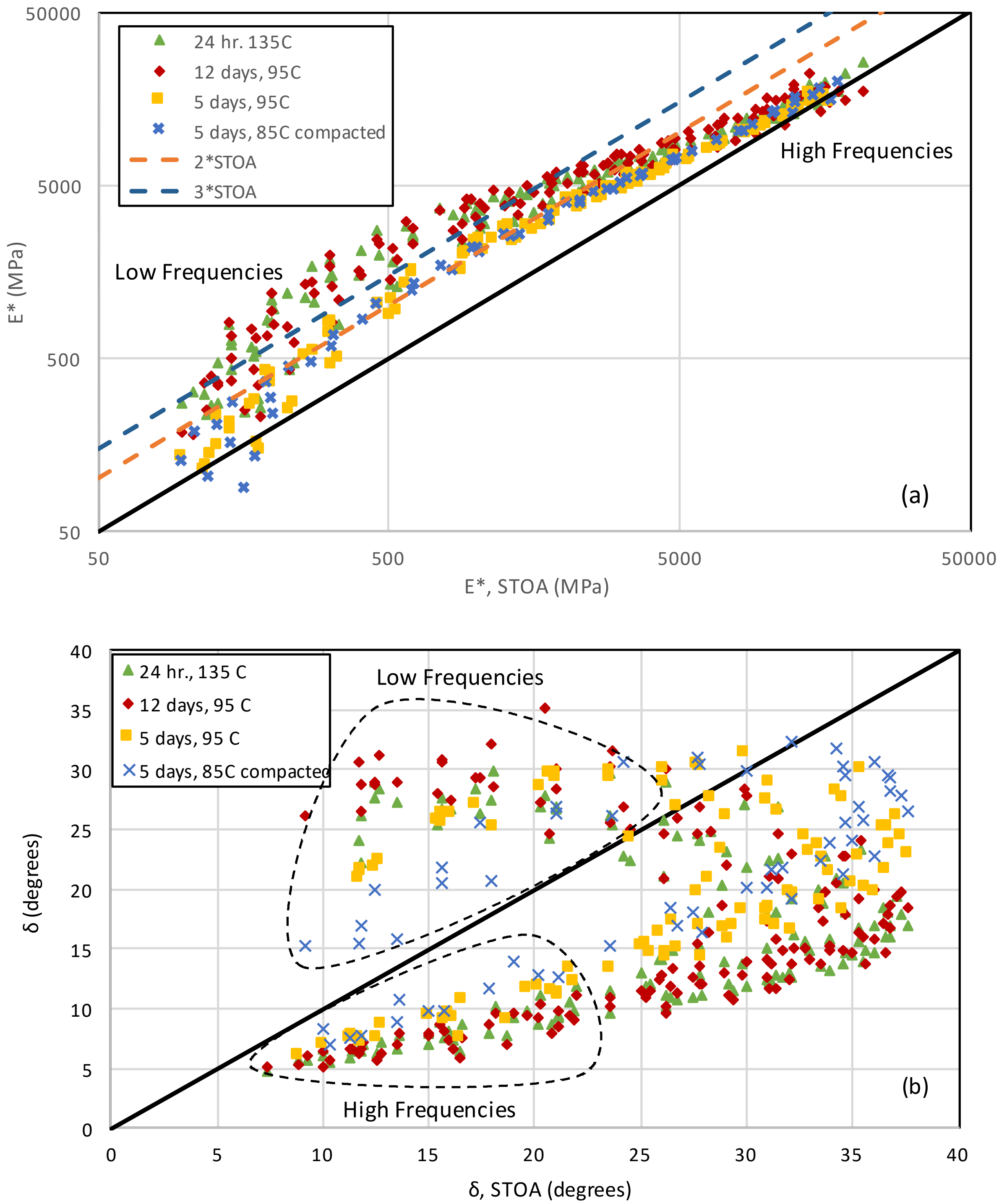


FIGURE 2 LVE Properties a) Dynamic Modulus, b) Phase Angle of LTOA Mixtures versus STOA Mixtures for

To capture the combination of stiffness and relaxation capability of mixtures in a single plot, Black space diagrams are shown in Figure 3. The figure shows how Black space curves move with additional amount of aging. The inflection point moves to the bottom left side as more aging occurs. The observations in Black space diagram can be used to estimate thermal cracking susceptibility of asphalt mixtures. Generally, a mixture with higher stiffness at a constant phase angle is expected to incur greater thermal stress values. If the relaxation capability (phase angle) of this mixture is lower, the mixture relieves the thermal stress at a lower rate, resulting in higher thermal cracking potential. In Figure 3, higher phase angle for STOA with decreasing phase angle values are seen for STOA condition as compared to long term aged condition at constant value of stiffness (|E*|). This indicates that even for same level of thermal stress, relaxation capabilities of asphalt mixtures would diminish with increasing aging levels. Thus, aged mixtures would be more prone to cracking at a lower cooling rate than short term aged mixtures.

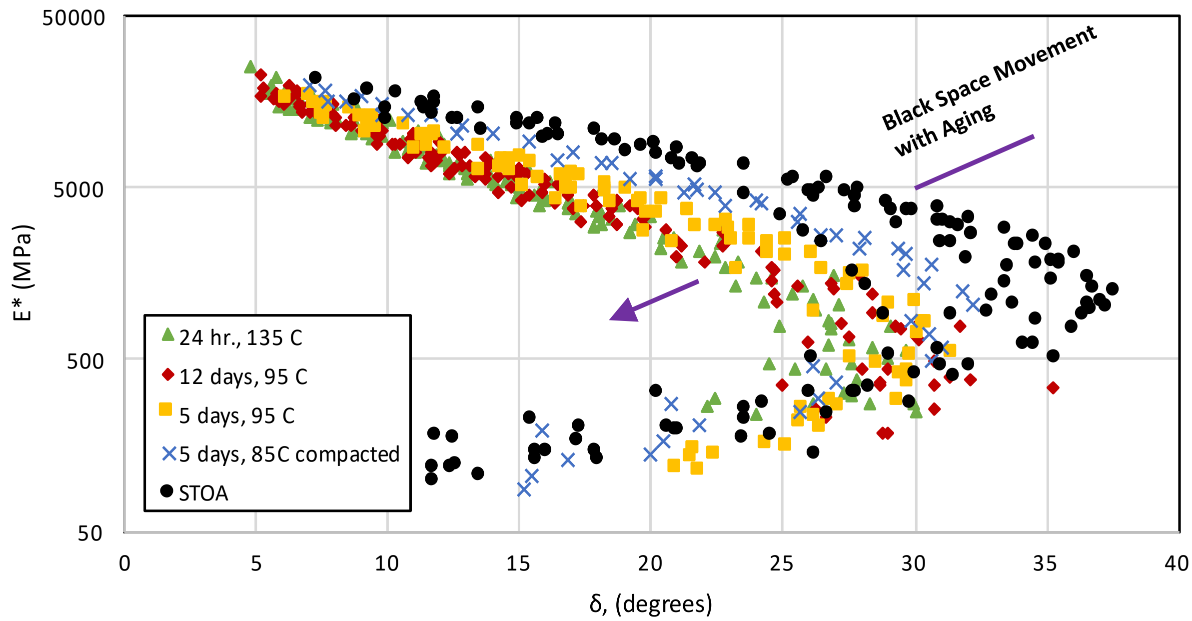


FIGURE 3 Black Space Diagrams of Different Aging Levels

Generally, a standard or generalized sigmoidal model is used to fit the dynamic modulus master curve. In this study, the standard sigmoidal model (Equation 1) is employed:

$$\log|E^*| = \delta + \frac{\alpha}{1+e^{\beta+\gamma\log(\omega)}} \qquad (1)$$

where $|E^*|$ is dynamic modulus, ω is frequency, and δ, α, β, and γ are the fit coefficients that describe the shape of dynamic modulus master curve. As the asphalt materials age, the shape of master curve changes, resulting in a variation in fit coefficients. Accordingly, these coefficients can be the indicators of aging level. The α and δ parameters are related to the equilibrium modulus (lower asymptote) and glassy modulus (upper asymptote) of master curve, respectively. The γ value controls the width of relaxation spectra, and the frequency of the inflection point can be calculated from $10^{-\beta/\gamma}$. As the asphalt material ages, the $|E^*|$ master curve tends to flatten and the inflection point is shifts to lower frequencies.

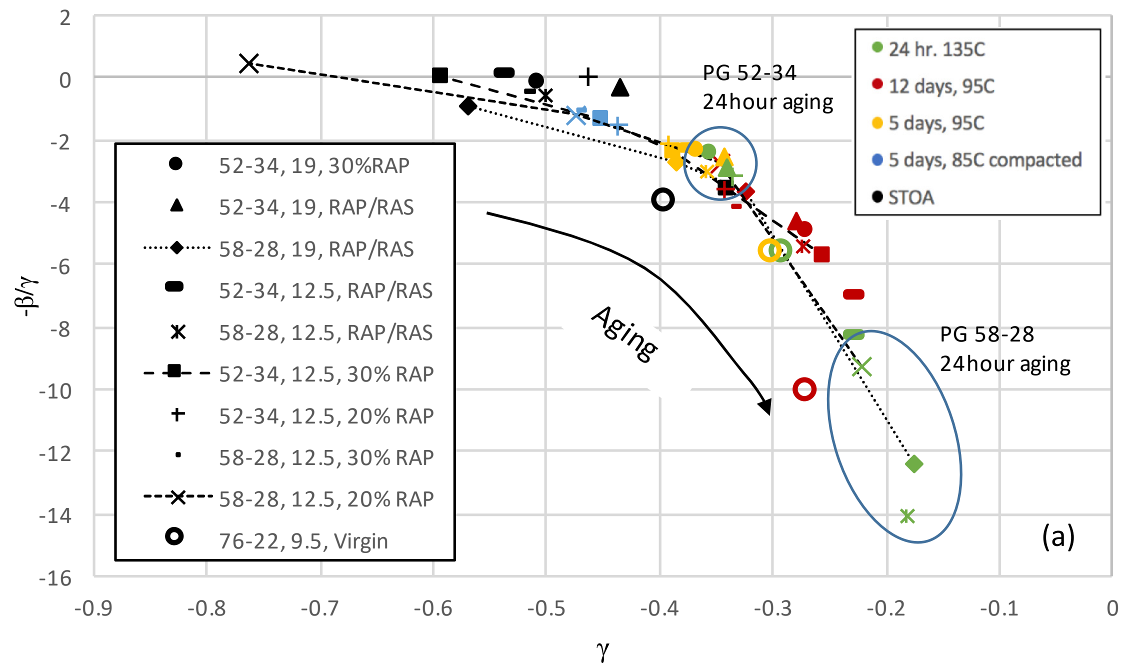
The inflection point parameter ($-\beta/\gamma$) versus relaxation spectra width parameter (γ) plot for mixtures (Figure 4a) is similar in concept to a crossover frequency versus rheological index (R value) plot for binders. The $-\beta/\gamma$ parameter

decreases and γ increases, moving points further towards the lower right as more aging occurs. The dashed lines connecting the points at different aging levels are drawn for three mixtures to show the trend from STOA to higher levels of aging. The parameter $-\beta/\gamma$ for all the short term aged mixtures (except virgin mix) is about zero. This parameter for 5 days compacted and 5 days loose aged mixtures varies between -1.1 to -1.5, and -2 to -2.9, respectively, while the variation of $-\beta/\gamma$ for two more severely aged mixtures (24 hour and 12 days) is greater. There is a gap between $-\beta/\gamma$ values of 24 hour aged mixtures which splits the mixtures into two groups. All the PG 52-34, 24 hour aged mixtures have higher $-\beta/\gamma$ than PG 58-28 mixtures, indicating less impact from aging on the viscoelastic properties for these mixtures. As a hypothesis, the severe conditioning of 135°C in a short duration (24 hours) might have different effects on mixtures with different binder grades than 12 days aging at the lower temperature. It should be noted that the results of binder testing on extracted and recovered binders from short term aged mixtures showed elevated zinc levels in two 19 mm mixtures with PG 52-34 binder, indicating that re-refined engine oil bottoms (REOB) may have been used in the production of the virgin binder. One of the concerns about using REOB in asphalt mixtures is that it might increase the aging of binder.

A Lorentzian equation (Equation 2) has been shown to accurately model the phase angle master curve and is used in this study.

$$\delta = \frac{a.b^2}{[(\log(\omega)-c)^2+b^2]} \qquad (2)$$

where δ is phase angle (degree), ω is frequency (Hz), and a, b, and c are the fit coefficients as follows: “a” shows the peak value, “b” controls the width of transition, and “c” is related to the horizontal position of the peak point. As the testing results show (Figure 1b), the phase angle master curves shift vertically and horizontally with different aging conditions. Therefore, the variation of vertical position of peak (a) and the parameter related to horizontal position of peak (c) were selected for aging evaluation and are designated as “vertical peak” and “horizontal peak”, respectively. Figure 5b shows how both vertical and horizontal peak values decrease with increased aging level, moving the points towards the bottom left of the plot. The plot can be an indicator of the relaxation capability of asphalt mixtures. The mixtures with higher horizontal and vertical peak values are expected to have higher relaxation capability and better fatigue and fracture behavior. Similar to what was observed with the dynamic modulus coefficients, for 24 hour aging, PG 52-34 mixtures (except PG 52-34, 12.5 mm, RAP/RAS) are separate from PG 58-28 mixtures with a higher horizontal peak value, shown with two circles in Figure 4a. The mixtures containing REOB (two PG 52-34, 19 mm mixtures) show lower vertical peak (a) values in all levels of aging. However, the decrease of horizontal peak (c) for these mixtures was less than the other mixtures.



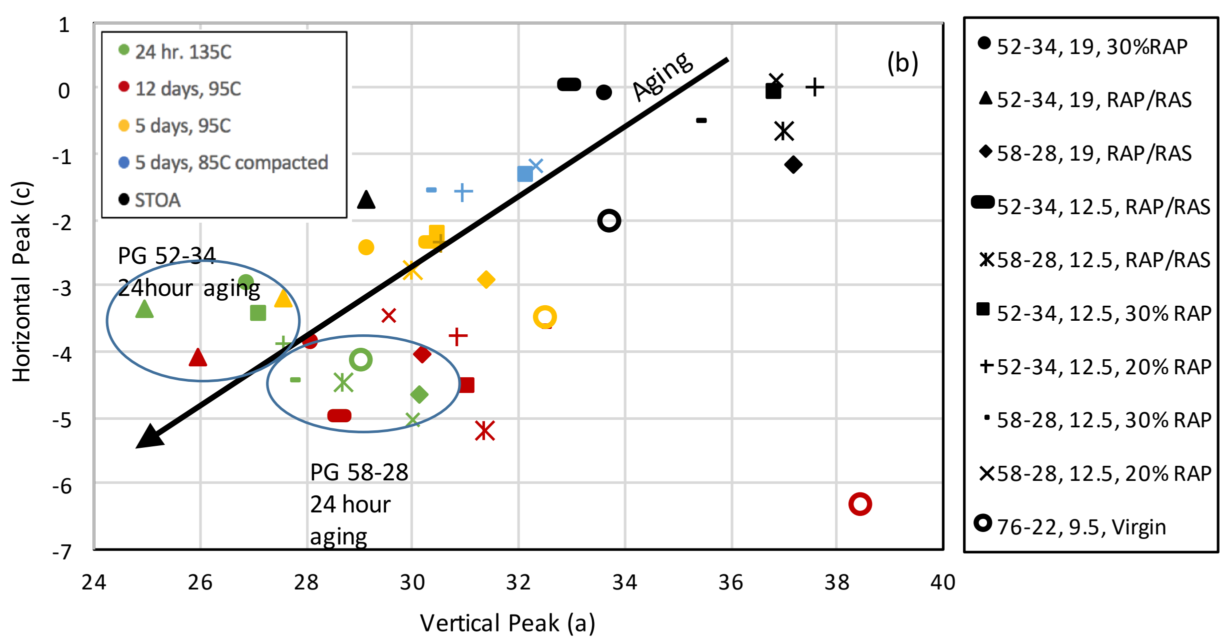


FIGURE 4 Shape Parameters: a) Variation of Dynamic Modulus Master Curve parameter b) Variation of Phase Angle Master Curve Parameters with Aging

Mensching et al. developed a parameter to evaluate the cracking performance of asphalt mixture in the format of the binder Glover-Rowe parameter ($\frac{|E^*|\cos\delta^2}{\sin\delta}$). In this study, the parameter is calculated at the temperature-frequency combination of 15°C-0.005 rad/s to be consistent with the binder Glover-Rowe parameter. The ratio of mixture G-R parameter in LTOA condition to the STOA condition is presented in Figure 5. As expected, the mixture G-R parameter increases as the level of aging changes from short term to intermediate and then to high aging levels, indicating higher susceptibility to cracking. There is a substantial increase in mixture G-R ratio when aging level increases from 5 days to 12 days at the same temperature. The intermediate aging levels increase the mixture G-R parameter from 1 to 3 times, but this ratio is from 3 to more than 7 for two high aging levels. This ratio is smaller for 19 mm, PG 52-34 mixtures (mixtures with REOB) and agrees with the variation of horizontal peak in Figure 4b.

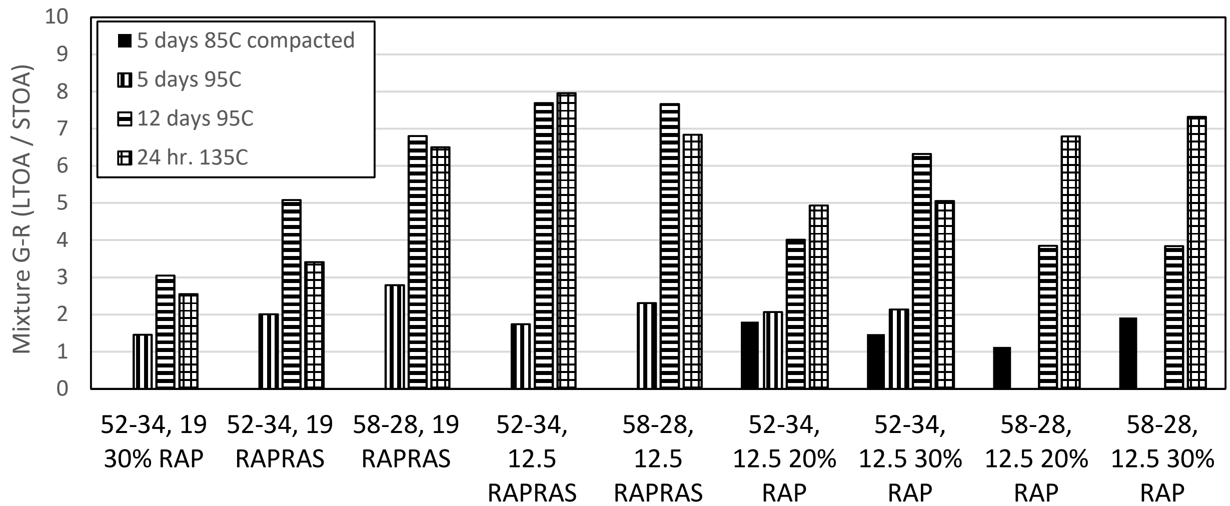
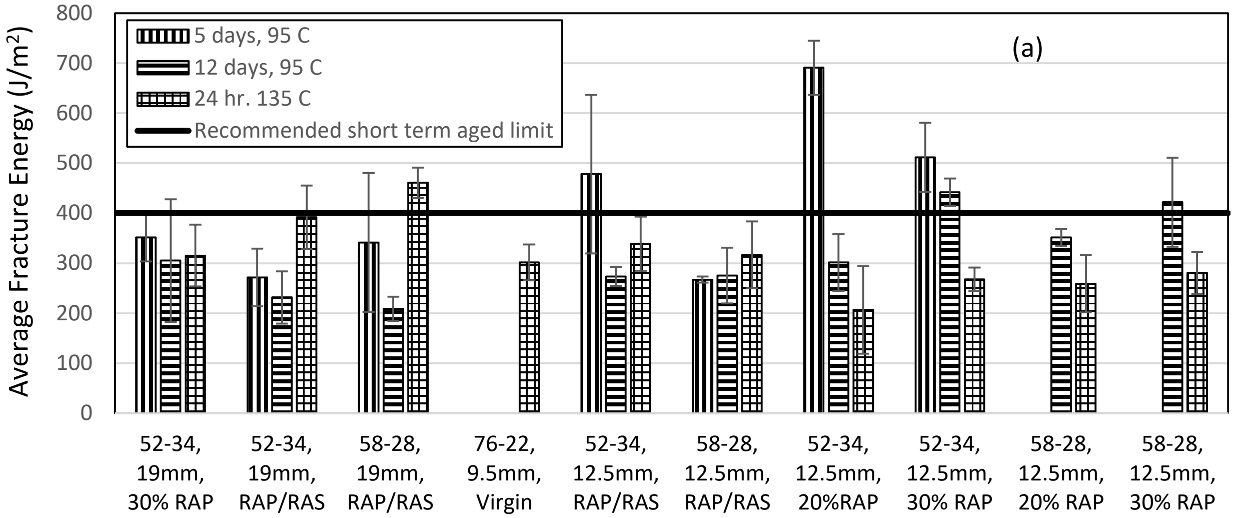


FIGURE 5 Ratio of Mixture G-R$_{LTOA}$ / Mixture G-R$_{STOA}$ (15°C and 0.005 rad/sec)

Fracture Parameters

The results of DCT and SCB fracture testing is presented and discussed in this section. Figure 6 shows the average fracture energy and fracture strain tolerance for the various mixtures at different aging levels. The error bars show the standard deviation of three replicates tested for each mixture. A threshold value of 400 J/m^2 for fracture energy of DCT has been proposed by previous researchers for short-term aged mixtures and is shown for visual comparison. Most of the high aged mixtures have the fracture energies less than this limit. There is not a significant difference between the fracture parameters of intermediate and high aging levels for two PG 52-34, 19 mm mixtures (with REOB). This agrees with the mixture G-R and phase angle shape parameters, indicating that the LVE and fracture properties of these mixtures do not increase much with aging. The trend of fracture strain tolerance (FST) is similar to fracture energy for these mixtures. For all the 12.5 mm only RAP mixtures, the trend is that both G_f and FST decrease when aging level changes from 5 days to 12 days, and 24 hour, while for the RAP/RAS mixtures, 24 hour mixtures show better fracture parameters than 12 days aged mixtures. The 24 hour aging level seems to be less detrimental to fracture energy than 12 days aging for all RAP/RAS mixtures. A potential reason for this behavior of RAP/RAS mixtures might be the greater amount of already aged and oxidized asphalt binder present in these mixtures, which is not as prone to a more severe aging temperature as other mixtures. There is a significant difference between the fracture properties of 5 days and 24 hour aging for PG 52-34, 12.5mm mixtures, while fracture energy and FST of 5 days aged, PG 58-28, 12.5mm, RAP/RAS mixtures are very close to those of high aged mixtures.



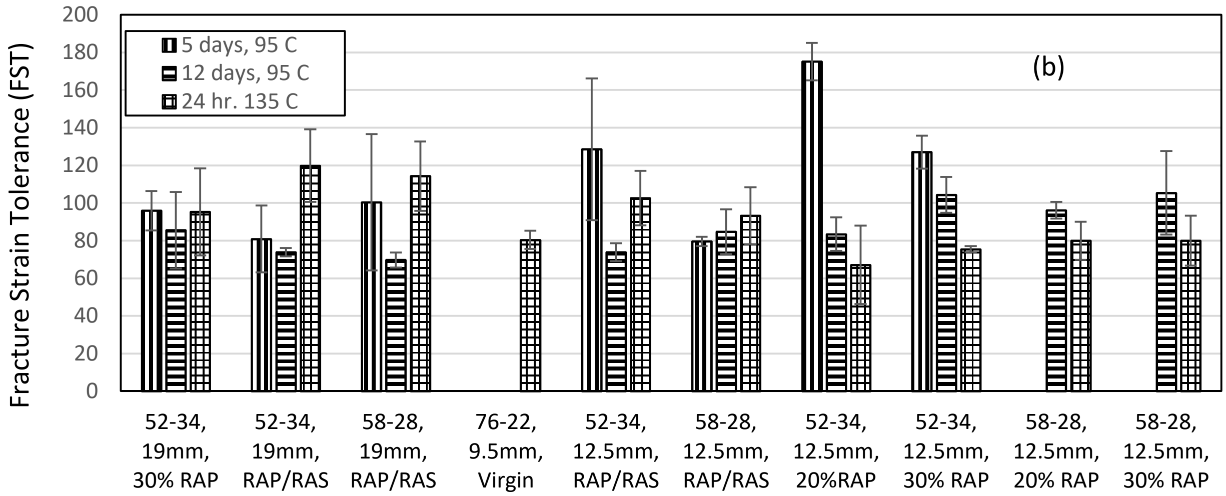


FIGURE 6 (a) Fracture Energy and (b) Fracture Strain Tolerance Values (DCT Testing)

Figure 7 shows the flexibility index (FI) parameter which is the average of 3 to 4 replicates for each mixture, with the standard deviation error bars. The FI values of 5 days aged mixtures are higher than 24 hour and 12 days aged values for all mixtures, with higher differences observed for RAP/RAS mixtures. The flexibility index of PG 52-34 mixtures is generally higher than the similar PG 58-28 mixtures, especially for 5 days aging level. The fracture properties obtained from SCB testing do not show a similar trend with the results of DCT testing. It is not surprising since the loading mode and testing temperature are different in these two fracture tests. Results shown here agree with recent work by Haslett et al. that showed that a single 25°C test temperature for SCB testing may not as clearly distinguish between mixtures with different low temperature binder grades.

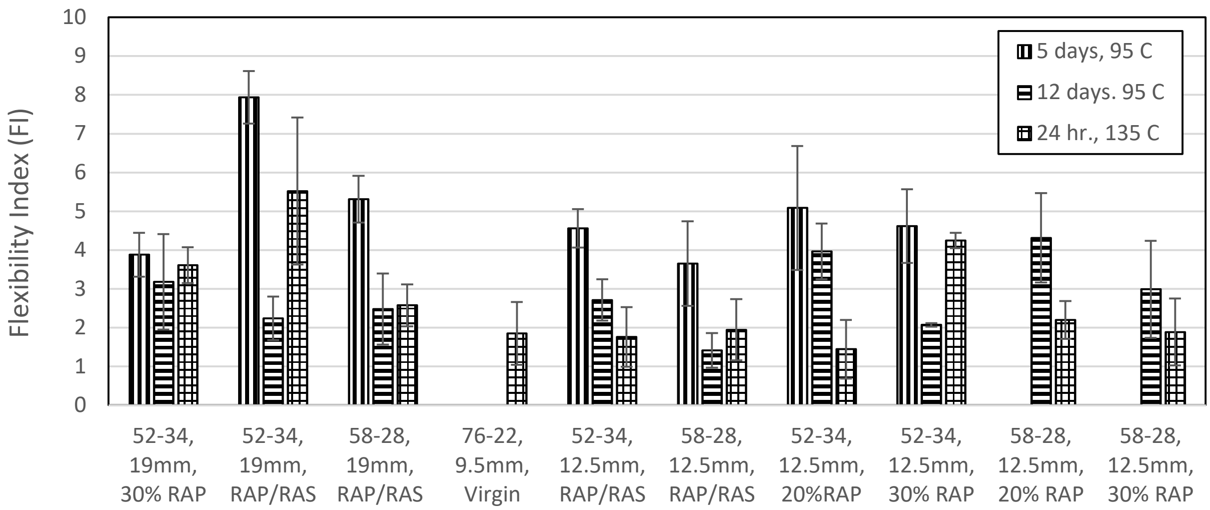


FIGURE 7 Average Flexibility Index Values (SCB Testing)